Quantum Dot Studies with COBRA: Imaging Buried Structures and Interfaces

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ABSTRACT

Quantum dots have sparked a remarkable amount of interest in device development and have initiated many studies of fundamental physics on the nanoscale. The peculiar properties of quantum dots arise from the confinement of charge carriers in three dimensions resulting in quantized energy levels seen in single atoms. In this study, we will investigate the use of a novel characterization tool, Coherent Bragg Rod Analysis (COBRA), to study the compostional and structural properties of InGaAs self assembled quantum dots grown on GaAs subtrates using Molecular Beam Epitaxy. COBRA has recently been demonstrated to be a powerful, if not indispensible tool, for probing buried structures and interfaces in a non-destructive way. The procedure involves obtaining real space electron density profiles of epitaxially or semi-epitaxially grown structures by transforming reciprocal space x-ray data. The information gained from this method will be used to improve the growth of quantum dot materials and correlate the structure and chemical composition of the dots with their physical properties.

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1. PROSPECTUS

1.1 Introduction and Motivation for Project

Quantum dots are interesting because of their fully quantized, tunable electronic states, high radiative efficiencies and their quasi-zero dimensional properties. From a device point of view, they have numerous benefits because they can be manufactured as buried structures in thin film semiconductor devices. Devices involving single dots have been either proposed or fabricated, as in the case of 2 level systems for quantum computing and single photon sources. Ensembles of QD's have been successfully used in the development of mid-infrared detectors, semiconductor lasers and solar panels, due to the low threshold currents, low temeperature sensitivity of the treshold current and high differential quantum efficiency [1, 2, 3].

The art of growing heterostructures containing quantum dots by Molecular Beam Epitaxy (MBE) has developed tremendously over the past decade. The need to develop techniques to characterize the QD growth cannot be overemphasized. Growers need to know what the optimum growth parameters are to produce these structures with the highest quality. From the view of fundamental sciences, characterizing these novel structures provides information vital to the understanding of both microstrutural growth and the unique optoelectronic properties of the dots which arise from processes on the atomic scale.

The traditional techniques for studying the structural properties of buried nanostructures, particularly, for Self Assembled Quantum Dots, include in-situstructural probes such as Reflection High Energy Electron Diffraction (RHEED) and Scanning Tunnelling Microscopy(STM) and ex-situ methods such as Atomic Force Microscopy (AFM) (which can also be implemented in-situ), Transmission Electron Microscopy(TEM) and Small Angle X-ray diffraction. RHEED and AFM are well suited for studying surface morphology and are not very effective for buried structures such as embedded QDs. Cross sectional STM is useful for studying buried interfaces but is limited to particular cleavage planes. High Resolution TEM can image atomic arrangements, however, it is limited by sample preparation since thin sections ($\approx 10nm$) are required to allow electrons to penetrate the sample. X-ray characterization techniques are advantageous for studying buried structures due to the relatively large penetration power of x-rays, however, most x-ray methods require model assumptions and fitting routines.

The Coherent Bragg Rod Analysis(COBRA) technique is a novel and powerful model-independent x-ray diffraction method which can be used to directly obtain three-dimensional electron density maps of epitaxial or semi-epitaxial thin films [4] by extracting phase information from reciprocal space x-ray scans. The technique has been applied mainly to study ferroelectricity in $PbTiO_3$ and $BaTiO_3$ thin films grown on conducting and insulating substrates [5]. In the area of semiconductors, the COBRA procedure has been used to successfully study the interface structure and composition in InAs/GaSb and GaSb/InAs systems[6]. Interesting and new insights into the Gd_2O_3 on GaAs system have also been reported using COBRA [4, 7]. Implementing the COBRA method for new systems such as quantum dots would hopefully result in helping us understand these systems in much more detail with atomic resolution. The coherent nature of QD's with respect to the substrates on which they are grown, make them an excellent candidate for COBRA studies.

This prospectus is organized as follows. First, a review of the current advances in the growth and characterization of Self Assembled Quantum Dots is presented. This is followed by an introduction to the Coherent Bragg Rod Analysis technique and a review of some of the current results which have been obtained using this technique. In the Plan of Study section, a summary of the goals we hope to achieve by studying Quantum Dots with the COBRA technique, and the anticipated challenges, are presented. Finally, the possible future directions of the project are outlined.

1.2 Background

1.2.1 Self Assembled Quantum Dots

Self assembled quantum dots, (SAQD) can be grown effectively by Molecular Beam Epitaxy (MBE) in the Stranski Krastanow growth mode. Stranski Krastanow growth is described as the formation of three-dimensional coherently strained islands from two-dimensional epitaxial thin films deposited on substrates with a large lattice mismatch [8, 9, 10, 11] as a mechanism to reduce strain. An example is the case of InAs on GaAs substrates where there is a 7% lattice mismatch between the film and the substrate. The islands spontaneously form to relieve mis-match strain when the thickness of the wetting layer (i.e. the deposited film) becomes greater than a critical thickness which is dependent on a number of factors including the shape and composition of the quantum dot and the growth conditions. This results in the transition of the 2D film to an array of quantum dots with good uniformity. Due to the large lattice mismatch of InAs on GaAs, the critical thickness for island formation can be as low as 1.7 monolayers(ML) as shown in Figure 1.1 [12, 13].

When the sizes of 3D islands are comparable to the deBroglie wavelengths of the carriers and to their mean free paths, the carriers are quantum confined in levels inside the QD's, hence, they are sometimes referred to as "artificial atoms". In the case of InGaAs with a deBroglie wavelength of 50nm, the SAQD's have been observed to have widths on the order of 20nm and heights on the order of 5nm. The shapes of these dots may be lenticular, conical, truncated conical, pyramidal or truncated pyramidal. QD's are usually capped to prevent contamination and oxidation. The prescence of the capping layer affects the composition and shape of the dots as well as the strain state[14].

Although total control of the growth of SAQD's has not yet been achieved, it is possible to obtain correlated dots with less than 10% dispersion in their size, shape and composition[15, 16].Tersoff et al. have demonstrated experimentally and theoretically that when successive layers of dots are grown, the island size and spacing become more uniform evolving into a more regular three-dimensional arrangement[17].

Structural Characterization of InAs/GaAs QD's

AFM and STM can be used to determine the shape and sizes of uncapped islands. Kolosov et. al. [18] have developed a modification of AFM called Ultrasonic Force Microscopy which makes the method also sensitive to strain and composition with 5nm spatial resolution. The tunnel current in STM is sensitive to material composition and strain, however, only conductive samples can be imaged. High resolution Cross Sectional STM (XSTM) of cleaved samples can be used to imaged buried structures with resolutions on the atomic scale. Lita et. al. [10] report significant In-Ga intermixing within InAs dots due to In surface segregation.

TEM is also used to image planar sections of buried heterostructures. The main limitations here again are that the island sizes measured may be inaccurate due to interaction of diffracted electrons with strain fields. The preparation of the sample for TEM is destructive and can disturb the structure and strain fields being measured. It is also not sensitive to chemical composition, unless some kind of analysis technique is used in conjunction with the TEM imaging (e.g. x-ray fluorescence or electron energy loss spectroscopy (EELS). Also, cross sectional STM and AFM require cleavage of the sample. Thus only certain planes where cleavage occurs are accessible to XSTM and AFM. Addtional outward strain relaxation of the islands does occur due to material removal during cleavage and thus, the interpretation of results has to be performed with care.[16]

A number of x-ray techniques have been used to study buried nanostructures including grazing incidence small angle x-ray scattering, x-ray reflectivity, grazing- incidence x-ray diffraction and anomalous x-ray scattering with particular sensitivity to strain. X-rays, as a result of their relatively large penetration power, permit the non-destructive study of buried structures, however, most x-ray techniques suffer from the limitation that since measurements are made in reciprocal space, model fitting usually with numerous free parameters [19, 20] is required to reconstruct the real space structures due to the challenges associated with extracting phase information. Robinson et. al. have successfully used phase reconstruction techniques to determine the shape and sizes of Au nanoparticles by oversampling the reciprocal space diffraction data with coherent x-rays. [21].

1.2.2 Composition and Strain in Self Assembled Quantum Dots

The islands form by depleting material from the wetting layer, thus, the composition of these islands tend to be different from the composition of the 2D films from which they form. In Tersoff's model of the nucleation of dislocation-free islands [22] from an alloy film such as $In_xGa_{1-x}As$, the free energy for an island formation is

$$E(x,V) = E_{surf}(x,V) + E_{mix}(x,V) + E_{strain}(x,V) - (V/V_a)[x\mu_A + (1-x)\mu_B] \tag{1.1}$$

where x refers to the atomic fraction of component A of an AB alloy, V is the volume of the island and V_a is the volume per atom. μ_A and μ_B are the chemical potentials of the components A and B respectively. E_{surf} is the surface energy (which is assumed to be independent of composition). E_{mix} is the free energy of mixing for the unstrained alloy and E_{strain} represents the elastic energy of the island. Island formation is assumed to occur when the free energy is sufficient to overcome a nucleation barrier. This barrier is the minimim nucleation energy and is obtained by minimizing the free energy with respect to x and finding the maximum with respect to V. It is found that alloy decomposition leads to a reduction in the nucleation barrier by 30%-85% although this prediction might be slightly altered by growth kinetics and mass transport mechanisms from the wetting layer and the substrate and in the case of embedded dots, the effect of the overlaying layers.

Joyce et. al. [23], based on XSTM results, suggest that in InAs/GaAs quantum dot systems, In and Ga interdiffusion as well as In segregation occur also as mechanisms to relieve mis-match strain. For example, in the growth of InAs on GaAs, Ga atoms diffuse into the InAs islands with Ga concentration varing continuously from 100% at the dot-substrate interface to 0% at the apex of the dot[19].

To account for the diffusion of Ga into InAs dots, Rosenauer et al.[24] propose based on TEM and photoluminiscence measurements that the segregation of In leads to the generation of vacancies within the metal sublattice. These vacancies are filled by the Ga atoms which diffuse from the GaAs buffer layer.

Lattice spacings and strain profiles have been found to be consistent with compositional variations and have been used indirectly in STM and x-ray measurements to determine concentration profiles within quantum dots. By studying the lattice spacings within $In_{0.5}Ga_{0.5}As/GaAs$ QDs. Liu et al. [25] de-

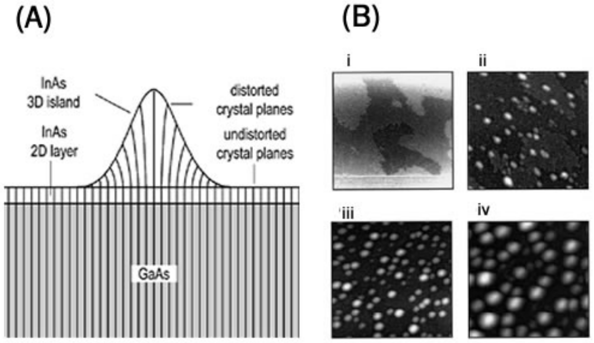

Fig. 1.1: (A) shows a schematic of the lattice distortion in a 3D InAs island. (B) shows STM imagecorresponding to a range of InAs depositions at 450 C for i)1.4 ML ii)1.7ML iii)2.0ML and iv)2.7 ML clearly showing the 2D to 3D transition after 1.4ML.[23]

termined using XSTM that the dots possessed In-rich cores with an inverted triangular shape with In fraction decreasing from center to edge and top to bottom of the dots. This profile is found to be independent of the island shape.

Kegel et al.[19] have successfully carried out surface x-ray diffraction studies and reported reliable results on shape, interdiffusion and strain profiles of free standing InAs/GaAs quantum dots with nanometer scale resolution. Their results were averaged over a $1mm^2$ area of free standing dots. They infer the interdiffusion of Ga into the dots from the curvature of isostrain areas. Their conclusion of lateral composition homogeneity within the dots is in contrast with the "inverted-cone In profile" presented by Liu et al.[25]. Given that segregation and interdiffusion are strongly dependent on the growth conditions, the differences might be accounted for; however, a more direct method for obtaining composition and strain information would lead to a better understanding of the compositions of these structures.

1.2.3 Coherent Bragg Rod Analysis

As mentioned earlier, most x-ray techniques are very model dependent and require many free fitting parameters for converting the reciprocal space information into real space. The Complex Scattering Factors (CSF) of any system have both an amplitude and a corresponding phase factor. If the phase and amplitude of the CSF of a system are known exactly, a three-dimensional real space electron density map of the system can be determined accurately by taking the Fourier transforms of the CSF's. However, during x-ray diffraction experiments, the squares of the CSF are measured as diffraction intensities and it becomes non-trivial to accurately retrieve the phases and amplitudes associated with the system. A number of phase retrieval procedures have been proposed including

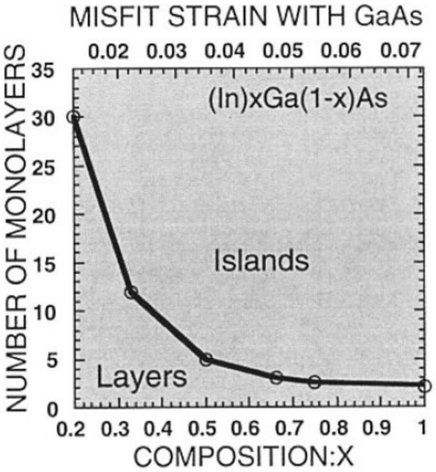

Fig. 1.2: Plot showing the number of $In_xGa_{1-x}As$ monolayers required for the transition from 2D to 3D growth as a function of composition for MBE deposited structures [13]

the recently developed Coherent Bragg Rod Analysis (COBRA) procedure[4, 5].

COBRA involves measuring the diffraction intensities along substrate defined Bragg Rods to determine the complex scattering factors from which the electron density can be obtained directly by Fourier transformations. COBRA assumes the measured total scattering factor $\vec{T}$ to be a coherent sum of scattering from a known reference electron density $\vec{S}$ and an unknown electron density $\vec{U}$. The reference may be the known substrate and a simple model for the film. At two adjacent points along a Bragg rod differing by $\Delta\vec{k}$

$$\vec{S}(\vec{k}-\frac{\Delta\vec{k}}{2})+\vec{U}(\vec{k}-\frac{\Delta\vec{k}}{2})=\vec{T}(\vec{k}-\frac{\Delta\vec{k}}{2}) \tag{1.2}$$

$$\vec{S}(\vec{k}+\frac{\Delta\vec{k}}{2})+\vec{U}(\vec{k}+\frac{\Delta\vec{k}}{2})=\vec{T}(\vec{k}+\frac{\Delta\vec{k}}{2}) \tag{1.3}$$

Since the film is confined in the one direction, it can be assumed that the CSF varies continuously along the Bragg rod. Also, since the unknown part of the CSF is confined mainly to an ultrathin region of the film and substrate close to the interface, $\vec{U}$ is expected to vary smoothly in reciprocal space so that:

$$\vec{U}(\vec{k}-\frac{\Delta\vec{k}}{2})\approx\vec{U}(\vec{k}+\frac{\Delta\vec{k}}{2})\approx\vec{U}(\vec{k})_a \tag{1.4}$$

and

$$|\vec{S}(\vec{k}+\frac{\Delta\vec{k}}{2})+\vec{U}(\vec{k})_a| = |\vec{T}(\vec{k}+\frac{\Delta\vec{k}}{2})| \tag{1.5}$$

$$|\vec{S}(\vec{k}-\frac{\Delta\vec{k}}{2})+\vec{U}(\vec{k})_a| = |\vec{T}(\vec{k}-\frac{\Delta\vec{k}}{2})| \tag{1.6}$$

The above assumption can be made if the reference system is chosen such that the scattering factors are of the same order of magnitude as the measured intensities and if the origin of the real space coordinate system is close to to the part of the unkown electron density and far from the part with the known electron density. The solution to equations 1.5 and 1.6 which gives the minimum change in $\vec{U}$ for two adjacent points in reciprocal space gives the correct unknown complex scattering factor since $\vec{U}$ is assumed to vary slowly along the Bragg rods. The total scattering factor is then recalculated using 1.2 and 1.3 and Fourier transformed to obtain the three dimensional electron density in real space.

Bragg rod measurements, therfore, can be used to determine the unknown electron density distributions for epitaxial and semi-epitaxial thin films using the COBRA formalism. The films are assumed to have two-dimensional periodicity within the plane of the film and aperiodicity in the perpendicular direction. Since the films studied in COBRA are epitaxial, the assumption can also be made that the first few monolayers of the film have 2D periodicity coherent with that of the underlying substrate. However, in the case where the film has a multiple period commensurate with the substrate, the film can be assumed to be folded in-plane by moving all atoms into one 2D substrate defined unit cell using unit cell vectors [7, 4].

1.2.4 Review of Systems Investigated with COBRA

COBRA was first used to study the atomic structure of Gd_2O_3 grown on (100)GaAs by Yacoby et al[7, 4]. Gd_2O_3 is an excellent passivation oxide for GaAs. They found out that the Gd_2O_3 stacking order was different from the bulk and similar to the stacking order of the underlying substrate as shown in Figure 1.3.

Ferroelectricity in perovskites such as $PbTiO_3$ and $BaTiO_3$ have been also extensively studied using the COBRA method [5, 26] to determine domain structure and the atomic displacements which lead to polarization.

Cionca et al. [6] have studied the compositions at the interfaces of InAs grown on GaSb(001) and GaSb grown on InAs(001) using COBRA as a first step to study semiconductor superlattice structures. By considering the sub-system close to the interface as a $Ga_mIn_{1-m}Sb_nAs_{1-n}$ quaternary, minimal segregation has been evidenced in InAs/GaSb(001) with a greater degree of "GaAs-like" bonds for the film grown under As_2(dimer) flux than the film grown under As_4 flux. Significant In and As interdiffusion is seen in the GaSb/InAs(001) also with a high degree of "GaAs-like" bonds at the interface.

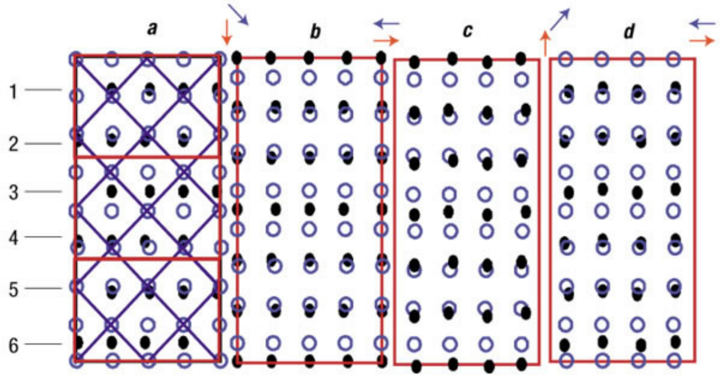

Fig. 1.3: In-plane Gd positions (dots) in four consecutive layers of the Gd_2O_3 film. Each large rectangle represents one 2D super-cell composed of 3 Gd_2O_3 cells (red) and 16 GaAs cells (blue). The positions of the substrate Ga/As atoms (circles) in four consecutive layers are shown superimposed. [7]

1.3 Plan of Study

A number of challenges arise when conducting diffraction experiments on an ensemble of particles with varying sizes and composition and non-uniform distribution. The probe beams commonly used in COBRA experiements are on the order of hundreds of microns while the average size and dot to dot spacings are on the order of tens of nanometres [9]. Thus, features such as composition and strain variations obtained in COBRA experiments would be averaged over the beam coverage area. The ideal situation would be one in which the dots have a high surface density and are identical in shape size and composition.

However, variations in the dots have to be expected [13]. It is worthwhile to explicitly state that the goal of the project would not be to characterize individual dots, but to obtain information related to the average behaviour of the dots. The information provided by COBRA would be the average displacement of atoms in the dot relative to positions of the substrate atoms as a function of the distance from the interface. The electron density profiles would also provide information on the atomic compositions witihin the dots as a function of the distance from the substrate-film interface.

Current advances in microfocusing of x-ray beams down to less than 100nm [27] exists using Fresnel zone plate optics and KirkpatrickBaez reflecting mirrors[28]. Suzuki et. al. report a 5% x-ray efficiency for producing 30nm spot sizes using the 3rd order focus of zone plates for 8keV x-rays. Stephenson et. al. also recently demonstrated focusing of 19.5 keV x-ray beams to 30nm with 44% efficiencies and presented theoretical calculations to suppport the possibility of reducing the spot size further to 1-5nm using Multilayer Laue Lens optics (MLL)

[29]. Although small focal spots of x-rays would permit single dot studies, the intensity suffers a drastic decrease. Reliable COBRA measurements require a dynamic range of about 3 orders of magnitude for relatively heavy atomic species such as In, Ga and As. [4]. the study of single dots would left for future studies as detector technologies such as pixel array detectors become more readily available. We plan on impementing an arrray detector for COBRA studies in the very near future for better signal to noise ratio and shorter acquisition times.

If the variations are expected to be centered around a mean set of parameters from one particle in the ensemble to another, then it is reasonable to assume that these deviations would be introduced as noise in the data obtained. Thus there would be a direct correlation between the particle variation and the noise. This would impose a limitation to what conclusions can be confidently extracted from the data interpretation. On the other hand, by pushing the COBRA technique to its limit, we would be gaining insight into the strength and inherent limitations of the technique.

1.4 Conclusions

The main aim of this study is to successfully image the interfaces and interiors of InAs/GaAs quantum dots using COBRA. To conduct this experiment, high brightness x-ray beams available at the Advanced Photon Source at the Argonne National Laboratory would be used. The analysis of the data obtained at the synchrotron would be carried out offline using the Matlab based COBRA analysis package developed by Yacoby et al.[4]. The information retrieved from the analysis of electron density maps from COBRA would be used to study the strain and composition profiles within the dots while paying particularly close attention to the dot/substrate interface.

The COBRA experiment would be coupled with other well established QD characterization techniques such as Atomic Force Microscopy and Transmission Electron Microscopy for comparison. Once we have demonstrated that imaging buried SAQD's is possible using the COBRA method, the next step would be to study the effect of growth parameters on the quality of the InGaAs SAQD's and the interfaces present in these heterostructures.

BIBLIOGRAPHY

[1] S. Franchi, G. Trevisi, L. Seravalli, and P. Frigeri. Quantum dot nanostructures and molecular beam epitaxy. *Progress in Crystal Growth and Characterization of Materials*, 47:166–195, 2003.

[2] Z. Mi, J. Yang, P. Bhattacharya, P. K. L. Chan, and K. P. Pipe. High performance self-organized InGaAs quantum dot lasers on silicon. *J. Vac. Sci. Technol. B*, 24(3):1519, 2006.

[3] Pallab Bhattacharya, David Klotzkin, Omar Qasaimeh, Weidong Zhou, Sanjay Krishna, and Donghai Zhu. High-speed modulation and switching characteristics of In(Ga)AsAl(Ga)As self-organized quantum-dot lasers. *IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS*, 6(3):426, May 2000.

[4] M. Sowan, Y. Yacoby, J. Pitney, R. MacHarrie, and R. Clarke et. al. Direct atomic structure determination of epitaxially grown films: gd_2o_3 on $gaas(100)$. *Phys. Rev. B*, 66(20):205311, 2002.

[5] D.D. Fong, C. Cionca, Y. Yacoby, and G.B. Stephenson. Direct structural determination in ultrathin ferroelectric films by analysis of synchrotron x-ray scattering measurements. *Phys. Rev. B*, 71:144112, 2005.

[6] C. Cionca, D.A. Walko, Y. Yacoby, C. Dorin, J. Mirecki Millunchick, and Roy Clarke. The Interfacial Structure and Composition of InAs and GaSb Thin Films Determined using Coherent Bragg Rod Analysis.

[7] Yizhak Yacoby, Mukhles Sowwan, Edward Stern, Julie O. Cross, Dale Brewe, Ron Pindak, John Pitney, Eric M. Dufresne, and Roy Clarke. Direct determination of epitaxial interface structure in Gd_2O_3 passivation of GaAs. *Nature Materials 1, 99101 (2002)*, 1:99–101, October 2002.

[8] T. Walther, A. G. Cullis, D. J. Norris, and M. Hopkinson. Nature of the Stranski-Krastanow Transition during Epitaxy of InGaAs on GaAs. *Phys. Rev. Lett.*, 86(11):2381, March 2001.

[9] E. Pehlke, N. Moll, A. Kley, and M. Scheffler. Shape and stability of quantum dots. *App. Phys. A*, 65:525, August 1997.

[10] B. Lita, R. S. Goldman, J. D. Phillips, and P. K. Bhattacharya. Interdiffusion and surface segregation in stacked self-assembled InAs/GaAs quantum dots. *App. Phys. Lett.*, 75(18):2797, November 1999.

[11] R. Notzel. Self-organized growth of quantum-dot structures. *Semicond. Sci. Technol.*, 11:1365–1379, June 1996.

[12] Grandjean N and J. Massies. Epitaxial growth of highly strained $\text{In}_x\text{Ga}_{1-x}\text{As}$ on GaAs(100): the role of surface diffusion length. *Journ. of Cryst. Growth*, 134:51, 1993.

[13] P. M. Petroff and S. P. DenBaars. MBE and MOCVD Growth and Properties of Self-Assembling Qunatum Dot Arrays in III-V Semiconductor Structures. *Superlattices and Microstructures*, 15(1):15, 1994.

[14] D. Zhi, H. Davock, R. Murray, C. Roberts, T.S. Jones, D.W. Pashley, P.J. Goodhew, and B.A. Joyce. Quantitative compositional analysis of inas/gaas quantum dots by scanning transmission electron microscopy. *J. Appl. Phys.*, 89:2079, 2001.

[15] J. M. Moison, F. Houzay, F. Barthe, L. Leprince, E. Andre, and 0. Vatel. Self-organized growth of regular nanometer-scale InAs dots on GaAs. *Appl. Phys. Lett.*, 64(2):196, January 1994.

[16] M.S. Skolnick and D.J. Mowbray. Recent developments in the physics and applications of self-assembled quantum dots. *Physica E*, (21):155 163, 2004.

[17] J. Tersoff, C. Teichert, and M. G. Lagally. Self-organization in growth of quantum dot superlattices. *Phys. Rev. Lett.*, 76(10):1675, March 1996.

[18] O. V. Kolosov, C. D. Marsh M. R. Castell, G. D. Briggs, T. I. Kamins, and R. S. Williams. Imaging the Elastic Nanostructure of Ge Islands by Ultrasonic Force Microscopy. *Phys. Rev. Lett.*, 81(5):1046, 1998.

[19] I. Kegel, T. H. Metzger, A. Lorke, J. Peisl, J. Stangl, G. Bauer, J. M. Garca, and P. M. Petroff. Nanometer-Scale Resolution of Strain and Interdiffusion in Self-Assembled $InAs/GaAs$ Quantum Dots. *Phys. Rev. Letters*, 85(8):1694, August 2000.

[20] J. Stangl, V. Holy, and G. Bauer. Structural properties of self-organized semiconductor nanostructures. *Rev. Mordern. Phys*, 76(3):725, July 2004.

[21] I. K. Robinson, I. A. Vartanyants, G. J. Williams, M. A. Pfeifer, and J.A. Pitney. Reconstruction of the shapes of gold nanocrystals using coherent X-Ray diffraction. *Phys. Rev. Lett.*, 87(19):195505, November 2001.

[22] J. Tersoff. Enhanced Nucleation and Enrichment of Strianed-Alloy Quantum Dots. *Phys. Rev. Lett.*, 81(15):3183, October 1998.

[23] P. B. Joyce, T. J. Krzyzewski, G. R. Bell, B. A. Joyce, and T. S. Jones. Composition of InAs quantum dots on GaAs(001)Direct evidence for (In,Ga)As alloying. *Phys. Rev. B*, 58(24):981, December 1998.

[24] A. Rosenauer, D. Gerthsen, D. Van Dyck, M. Arzberger, G. Bohm, and G. Abstreiter. Quantification of segregation and mass transport in $In_xGa_{1-x}As/GaAs$ Stranski-Krastanow layers. *Phys. Rev. B*, 64(24):245334, 2001.

[25] N. Liu, J. Tersoff, O. Baklenov, Jr. A. L. Holmes, and C. K. Shih. Nonuniform composition profile in in0.5ga0.5as alloy quantum dots. *Phys. Rev. Lett.*, 84(2):334, January 2000.

[26] Codrin Cionca. *Imaging Interfaces in Epitaxial Heterostructures.* PhD thesis, University of Michigan, 2005.

[27] Yoshio Suzuki, Akihisa Takeuchi, Hidekazu Takano, and Hisataka Takenaka. Performance test of fresnel zone plate with 50nm outermost zone width in hard x-ray region. *Jpn. J. Appl. Phys.*, 44(4A):1994, 2005.

[28] O. Hignette, P. Cloetens, G. Rostaing, P. Bernard, and C. Morawe. Efficient sub 100 nm focusing of hard x rays. *Rev. Sci. Instrum.*, 76(6):63709, 2005.

[29] H. C. Kang, J. Maser, G. B. Stephenson, C. Liu, R. Conley, A. T. Macrander, and S. Vogt. Nanometer linear focusing of hard x rays by a multilayer laue lens. *Phys. Rev. Lett.*, 96(12):127401, March 2006.